Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 41 (2012) 1647 – 1653

Engineering Procedia

www.elsevier.com/locate/procedia

International Symposium on Robotics and Intelligent Sensors 2012 (IRIS 2012)

Capability Assessment of Finite Element Software in Predicting the Last Ply Failure of Composite Laminates

Norzihan Rahimi, Ahmad Kamil Hussain, Mohd Suhairil Meon, Jamaluddin Mahmud*

Faculty of Mechanical Engineering, Uinversiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

Abstract

Finite element programming using language such as FORTRAN, C++ and MATLAB has been the common and traditional tool to perform the progressive failure analysis of composite structures. This procedure requires high programming skills and strong mathematical understanding. This paper for the first time assesses the capability of a commercially available finite element analysis (FEA) software, ANSYS, to perform the Last Ply Failure (LPF) analysis of a laminated composite plate. The analysis is carried out by employing Maximum Stress and Tsai-Wu failure criteria. It is modelled and performed using ANSYS software which has a feature that supports the failure criteria and analysis procedure. The feature allows determination of maximum strength on individual layers in a composite laminate, thus provide an easier way to predict the failure progression. Based on analysis, the ultimate failure load and failure curves (LPF) are determined. The failure curves are compared and discussed with respect to previous experimental and FEA (both LPF and FPF) works. The results show that the LPF curves are very close to experiment that exhibits average errors as low as 16 %. Finally, it can be concluded that the ANSYS software is applicable in predicting an accurate composite laminate LPF.

Keywords: Laminated composite, LPF, FEA, ANSYS

Nomenclature

a	length of plate
h	laminate thickness
s	aspect ratio
u, v, w	translational displacement on x-, y-, z-axis direction
S	shear strength
X	longitudinal strength
Y	tranversional strength
Greek symbols	
θ	fiber angle direction
ν	Poisson's ratio
Subscripts	
C	compressive stress
T	total number of plies/ tensional stress
1,2,3	principal axes in 1-, 2-, 3- direction

* Corresponding author. Tel.: +603-5544-2823; fax: +603-5544-2821.
E-mail address: jm@salam.uitm.edu.my

1877-7058 © 2012 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
doi:10.1016/j.proeng.2012.07.363

1. Introduction

Composite material offers excellent material properties due to the high stiffness and strength-to-weight ratio. The applicability of composite materials has increased the demand for high reliability materials in various growing industries, for example aerospace, automotive and aircraft. The capability of composite structure in withstand with critical loading can be evaluated either by physical testing or any advance computational method.

A laminated composite is regarded failed when any of these appears; rupture of fiber, cracking of the matrix, debonding of fiber and matrix, or ply delamination [1]. All of those could occur in any ply in the laminate, and the weakest which fails first is considered as the first ply failure (FPF). The failure will further propagate to the next weakest plies available until it finally leads to the total rupture when the last ply fails. While the first ply failure analysis often overlooks the consequence of individual failure, determination of last ply failure (FPF) depends greatly on it [2].

Physical tests on composite structures are destructive and costly but the obtained strength values are based on last ply failure of the laminates only [3]. Thus, implementation of predicting tools i.e computer analysis softwares is preferable to analyze the failure of a structure beforehand. However, composite laminates analysis often dealt with complex computational method and immense mathematical analytic that are tedious and delicate. It requires repetitive or iteration of calculations with subject to varying load conditions, material properties and the geometry of the laminate itself [4]. Thus, finite element (FE) model development and analysis via commercial softwares is much preferred by researchers [3, 4]. FE model is developed by programming languages, computational tools and code generation by algorithms that function efficiently on computers [5]. The use of FEA in predicting the failure of laminated composites requires further research to provide an acceptable accuracy when compared with experimental results.

Recently, laminate analysis is made available on some software packages and capable of providing various computational requirements for solution [6]. For example, the ANSYS software developer had embedded the First-order shear deformation theory (FSDT) in to establish finite element models for free vibration analysis. The improved lamination theory, Higher-order Shear Deformation Theory (HSDT) also has been developed, and it removes the earlier assumption applied in FSDT for more accurate deformation [4]. Though, HSDT requires complex programming and not applicable in ANSYS for the time being.

Soni, as cited by Tolson et. al. has conducted an physical experiment [2, 7] to investigate the failure of T300/5208 graphite-epoxy composite with $[\theta_4/0_4/-\theta_4]_s$ laminate scheme and plotted a benchmark failure curved in which many of literatures in this paper are referring to [3, 6, 8]. The later Tolson et. al compared the FPF and LPF analysis under Hoffman, Lee, Hashin and Maximum Stress Failure Theory [2]. They introduced a seven degree of freedom FE model for $[\theta_4/0_4/-\theta_4]_s$ stacking sequence. In addition, Rahimi et. al further performed HSDT FPF analysis under Tsai-Wu and Maximum Stress Failure Theory and compared them under previous failure curve plotted by Tolson et. al [6]. Tsai-Wu failure theory is a well known polynomial theory in predicting composite laminate failure. The drawback of Tsai-Wu theory is that it could not identify modes of failure as compared to the interactive failure criteria, Maximum Stress Theory [8, 9].

This study further extends the work of Rahimi et. al. [6] which makes use of a robust and flexible FE programme that is able to perform an accurate laminate analysis. Besides, it could determine the failure curves of a selected lamination scheme using diverse failure criteria and lamination theories as to compare to other researchers' work [6, 10]. It simulates the similar LPF analysis using the built-in failure criteria functions provided by ANSYS. This paper for the first time assesses and compares the accuracy and practicality of a composite laminate failure behaviour approach using several combinations of finite element implementation (ANSYS) and failure criteria. This is novel as no similar approach has been reported.

2. Methodology

The numerically calculated LPF result for uniaxial tension of composite laminate are compared to data obtained by Sony from a similar experiment and extends the first ply failure analysis from Rahimi et. al. [6, 11]. This analysis is performed using a one eight-noded element plate model subjected to uniaxial tension. The procedure of the current study is represented in flow chart (Fig.1), comprises of three stages as described below:-

i). Finite Element model validation
ii). Last Ply Failure Analysis using ANSYS
iii). Error analysis and evaluation failure criteria

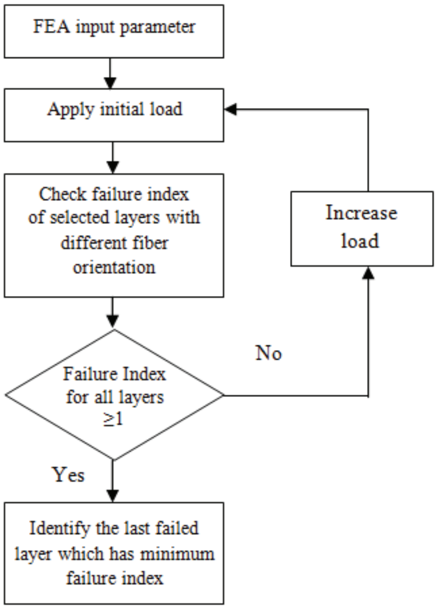
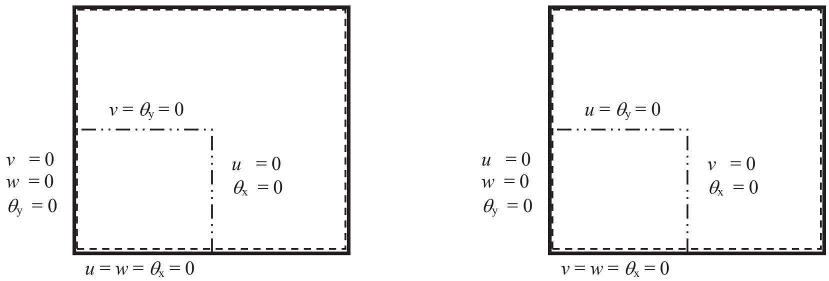


Fig. 1: Process flow of the LPF analysis

2.1. Finite element model validation

SHELL181 element type model is constructed using ANSYS (v12.1, 2009 SAS IP, Inc) based on plate geometry of 9 x 5 in^2, with thickness of each ply, h_i as 1.27 x 10^{-3} m/ply and its boundary condition as in Fig. 2. The model is set as a laminated composite plate with several lamination schemes which is either a cross-ply or an anti-symmetric angle ply. T300/5208 graphite-epoxy composite is selected as the material for the model and its mechanical properties are tabulated in Table. 1. The analysis is validated by executing it under transverse loading. As a result, their maximum deformation in z-axis is obtained and recorded. To validate the numerical solutions, this finite-element results are compared with exact solution as presented in Table. 2 [2].



(a) Cross-ply laminates (b) Anti-symmetric angle ply

Fig. 2: The simply supported boundary conditions for full-plate and quarter-plate model of cross-ply and anti-symmetric angle-ply laminates

Table. 1: Material properties of T300/5208 graphite-epoxy composite material

Properties	Values
E_1	132.4 GPa
$E_2 = E_3$	10.76 GPa
$G_{12} = G_{13}$	5.65 GPa
G_{23}	3.38 GPa
$\nu_{12} = \nu_{13}$	0.24
ν_{23}	0.49

Table 2: Comparison of exact and finite-element solution, z-displacement (m) for laminated composite plate (0.229 x 0.127 m^2)

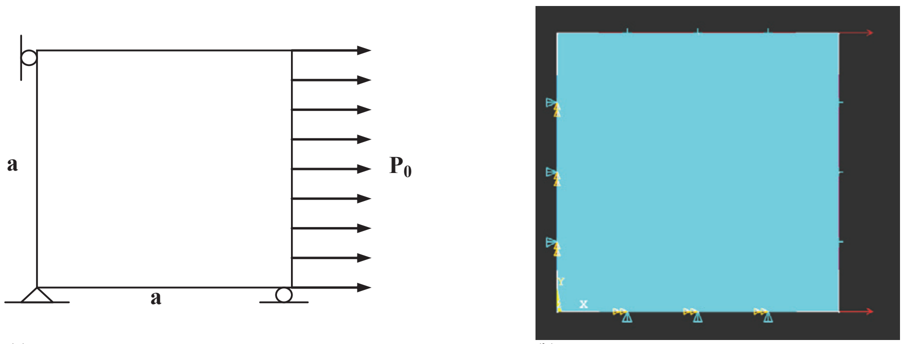
Lamination scheme	Type of Laminate	UDL (N/m^2)	Exact Solution	ANSYS	% Error
$[0/90]_T$	cross-ply	689.5	0.04785	0.04790	0.10
$[0/90/0/90]_T$		689.5	0.00340	0.00343	0.88
$[0/90/90/0]_T$		689.5	0.00582	0.00584	0.34
$[45/-45/45/-45]_T$	anti-symmetric angle ply	689.5	0.00276	0.00277	0.36
$[15/-15/15/-15]_T$		689.5	0.00639	0.00640	0.16
$[45/-45]_T$		689.5	0.04066	0.04070	0.10
$[15/-15]_T$		689.5	0.06610	0.06620	0.15

As could be observed in Table 2, ANSYS numerical FE results are close to the exact solution within an acceptable range i.e. less than 1.0%. Thus, this model is considered valid and applicable for the next LPF analysis.

2.2. Last Ply Failure Analysis using ANSYS

Tensile test is performed to determine the maximum uniaxial loading that a specimen could withstand, in which in our case is the strength of the plate. Applying stress beyond the maximum loading will cause the plate to undergo structural failure. In this study, LPF for laminated composite plate is considered has taken place when failure index of any layer is larger or equal to one.

The study replicates the experiment conducted by Soni as a computer model using ANSYS. This could allow comparison and evaluation of the current simulation results. Therefore, a simply supported composite plate under uniaxial tension consists of 24 layers, where the layup is $[\theta_4/0_4/-\theta_4]_s$ is modelled as in Fig. 3. The plate is square in shape, made of T300/5208 graphite-epoxy and having an aspect ratio (s = a/h) of 150. The material and strength properties of the composite are shown in Table 3.



(a) (b)

Fig. 3: Uniaxial tension model (a) schematic model (b) FE model (ANSYS)

Table. 3: Material properties for T300/5208 graphite-epoxy composite (Reddy and Pandey)[11]

E_1	= 138 GPa	X_T	= 1035 MPa
$E_2 = E_2$	= 10.6 GPa	X_C	= 1035 MPa
$\nu_{12} = \nu_{13} = \nu_{23}$	= 0.3	Y_T	= 27.6 MPa
$G_{12} = G_{13} = G_{23}$	= 6.46 GPa	Y_C	= 138 MPa
		S	= 41.4 MPa

FE procedure in ANSYS is carried out where the prediction of failure is based on its built-in failure theory and failure criteria functions i.e. Maximum Stress and Tsai-Wu. Incremental in load is applied until the whole layers failed. The maximum stress output of the last ply is the LPF value for each lamination scheme.

2.3. Error analysis and evaluation of failure criteria

The results produced by the FE implementations using ANSYS are compared with the experiments results from Soni [7]. The accuracy of results (predicting the FPF loads using FE procedures) is measured computing the percentage of difference, as in Eq. (1). The experiments results are taken as the reference.

$$\text{Difference} = \frac{\text{FE Result - Experimental Result}}{\text{Experimental Result}} \tag{1}$$

3. Results and discussion

Outcome of the analysis are demonstrated in the plotted failure curve below (Fig. 4) along with experimental value and previous FPF analysis [6, 8]. It is observed that the LPF failure curves for Tsai-Wu and Maximum Stress Theory are close to each other, except at 15^{o} fiber orientation. At this point also is where all of the analysis values are significantly larger than the actual experimental value i.e. 850 Mpa. The disagreement between those analyses and experimental value at 15^{o} has also been discussed earlier by Soni and Tolson et. al. where the free-edge delamination mode is neglected in the programming [7, 8].

It is noted that FPF and LPF for Maximum Stress failure criteria at 15^{o} are nearly overlapping, with value of 1477 Mpa and 1473.75 Mpa respectively. Furthermore, Tsai-Wu failure criterion shows the same trend where value of each FPF and LPF are relatively close to each other i.e 1324 Mpa and 1267.5 MPa respectively. These cases are due to the relatively lower difference in θ with respect to 0^{o} where the loading on the fiber orientation, θ, is most likely as the one in 0^{o} direction. Therefore the first ply and last ply fail at quite the same instant. This condition is reasonably applied to all cases less than 15^{o}.

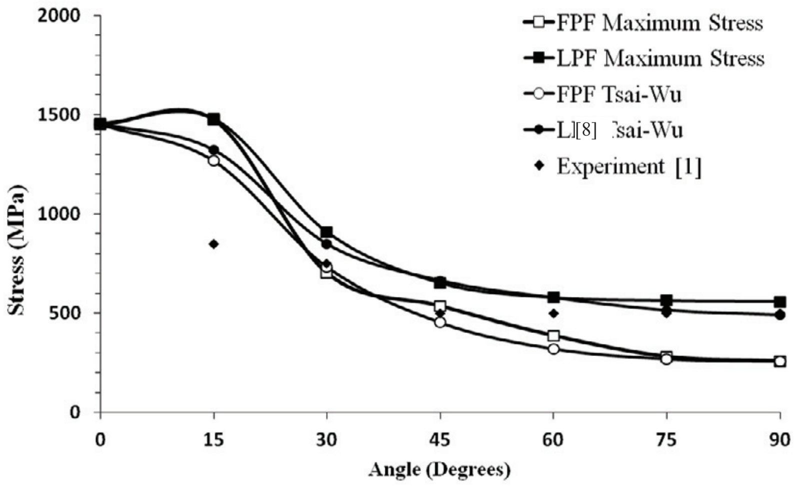


Fig. 4: LPF failure curves compared to Experiment [5] and FPF failure curves [11]

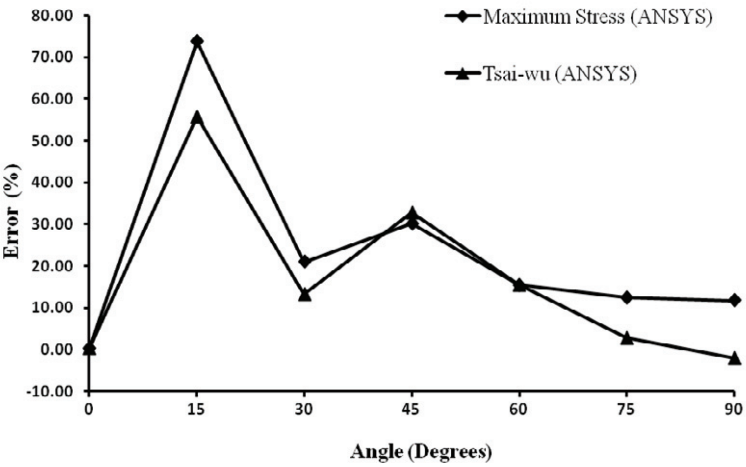


Fig. 5. Difference (%) curves of LPF composite laminate compared to Experiment [7]

In overall, it is evident that LPF values are higher from its corresponding FPF values, for both criteria. Even more, the differences between LPF values for both criteria and its experimental data are smaller in comparison to FPF analysis with the exception for 15^o and 30^o cases (as shown in Table 4). The average difference between the actual strength of the composites and LPF for Tsai-Wu criterion is 16.89% and it is lower than the Maximum Stress criterion's i.e. 23.58%. This is somewhat prove that the LPF analysis generally is more accurate to predict the actual failure stress than the FPF, specifically under the Tsai-Wu failure criterion.

Table 4: Difference (%) of FPF and LPF with reference to Soni's experiment [8]

	Maximum Stress				Tsai-Wu			
	Failure Stress		% Difference		Failure Stress		% Difference	
Experiment [8]	FPF	LPF	FPF	LPF	FPF	LPF	FPF	LPF
1450	1450	1455	0.03	0.35	1450	1455	0.03	0.35
850	1474	1477	73.38	73.76	1267	1324	49.12	55.74
750	701	908	6.50	21.00	733	849	2.20	13.20
500	536	651	7.25	30.20	454	664	9.25	32.75
500	387	578	22.60	15.50	321	578	35.80	15.50
500	281	563	43.75	12.50	270	514	46.00	2.75
500	259	559	48.25	11.75	259	490	48.25	-2.05
Average % Difference			28.82	23.58			27.24	16.89

4. Conclusion

The application of numerical analysis using commercial software (ANSYS) to predict the failure of composite laminates under uniaxial tension up to the last ply failure, LPF has been accomplished. In ANSYS, the failure results are based on the available built-in failure criteria i.e. Maximum Stress and Tsai-Wu. The failure curves comparison between previous works and this study had been plotted. LPF analysis was found to be accurate to its experimental value. In specific, LPF under Tsai-Wu failure criteria results in more exact prediction as compared to Maximum Stress failure criteria.

Completion of the study would benefits in designing and optimizing of a fiber reinforced composite laminate structures via computational softwares. Besides, the determination of maximum stress at each layer is made easier by the built-in failure criteria features and helps to understand the progressive failure mechanism especially. Further study could includes intensive FPF and LPF analysis on different angles effects, addition of failure criteria such as Hoffman's, Lee's and Hashin's, and implementing the improved lamination theory i.e. HSDT for LPF analysis by developing a FE program using FORTRAN.

Acknowledgment

This research is supported by the Ministry of Higher Education of Malaysia and Universiti Teknologi MARA Malaysia, grant no 600-RMI/ST/FRGS 5/3/Fst (157/2010).

References

[1] Agarwal, B. D., Broutman, L. J., 1980. Analysis and Performance of Fiber Composites. John Wiley, New York.
[2] Tolson, S., Zabaras, T., 1991. Finite Element Analysis of Progressive Failure in Laminated Composite Plates. Computers and Structures, 38, p. 361.
[3] Mahmud, J., Ismail, A. F., and Pervez, T., 2005. Employing a Failure Criterion with Interaction Terms to Simulate the Progressive Failure of Carbon-Epoxy Laminates. IEM Journal 66, p. 6.
[4] Zhang, Y. X., Yang, C. H., 2009. Recent Development in Finite Element Analysis for Laminated Composite Plates. Composite Structures, 88, p. 147.
[5] Liu, P. F., Zheng, J. Y., 2010. Recent Developments on Damage Modeling and Finite Element Analysis for Composite Laminates: A Review. Material and Design, 31, p. 3825.
[6] Rahimi, N., Musa, M., Hussain, A. K., Mahmud, J., 2012. Finite Element Implementation to Predict the Failure of Composite Laminates Under Uniaxial Tension. Advanced Materials Research, Vol. 499, pp. 20-24
[7] Soni, S. R., 1983. “A New Look at commonly Used Failure Theories in Composite Laminates”. 24th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Material Conference, p.171.
[8] M.N. Nahas, 1986. Survey of Failure and Post-Failure theories of Laminated Fiber-Reinforced Composites. Journal of Composites Technology and Research, 8, p. 138.
[9] Feng, Z., Yang, Q., Yin, X., Chen, Z., Zou, T., 2011. Failure Factor Research of Composite Laminates Containing Holes Based on MSC.Nastran. Advanced Materials Research, 160-162, p. 71.
[10] Tay, T. E., Liu, G., Tan, V. B. C., Sun, X. S., Pham, D. C., 2008. Progressive Failure Analysis of Composites. Journal of Composite Materials, 42, p. 1921.
[11] Reddy, J. N., Pandey, A. K., 1987. A first ply failure analysis of composite laminates. Computer and Structures 25 (3), p. 371.